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Dedicated to Professor Ionel Haiduc
on the occasion of his 65th birthday

REDUCTIVE AMINATION OF METHYL ETHYL KETONE OVER SUPPORTED GROUP VIII NOBLE METAL CATALYSTS

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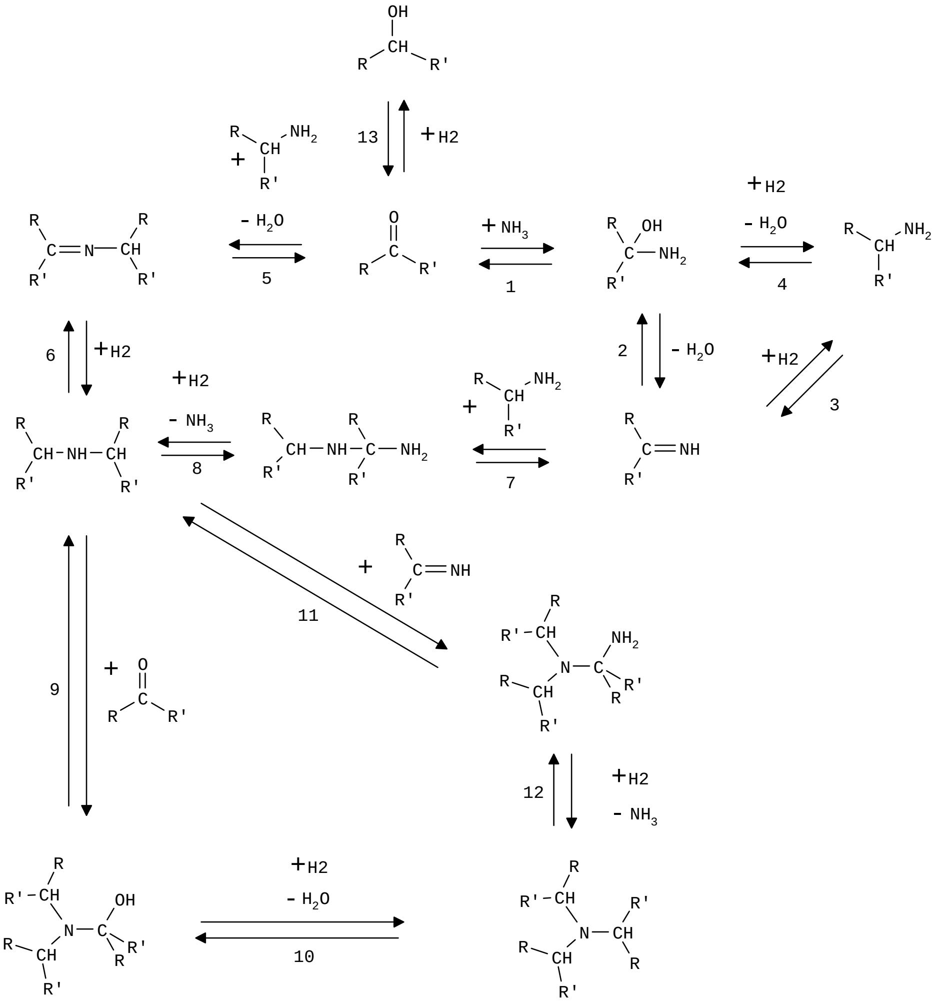
ABSTRACT. Reductive amination of methyl ethyl ketone (MEK) with ammonia (at ammonia/MEK molar ratios of ~ 14.5) and hydrogen has been performrd at 50 bar and 323-353 K over graphite and charcoal supported noble metal catalysts. Rhodium and platinum based catalysts showed the highest activity in reductive amination of MEK. The rhodium catalysts had high selectivity towards primary amine (sec-butylamine), while the platinum catalysts towards secondary amine (di-sec-dibutylamine). Tertiary amine (tri-sec-butylamine) was not detected in reaction products. The BET area and metal dispersion was found to have a pronounced influence on activity and selectivity.

Keywords: Reductive amination, Methyl ethyl ketone, Noble metal catalysts

INTRODUCTION

The reductive amination of aldehydes and ketones is an important synthetic route to amines. The reaction proceeds through an intermediately formed imine, hydrogenated with the help of a reducing agent or with molecular hydrogen in presence of a catalyst. Scheme 1 represents a non-exhaustive network of reactions (catalytic and non-catalytic) that could take place during reductive amination.

The addition of ammonia to the carbonyl compound results in aminoalcohol (1). This may be dehydrated to imine, which is subsequently reduced (2-3), or can be directly reduced to the amine (4). The primary amine formed can also behave as an aminating agent for the carbonyl compound, forming Schiff bases, which are reduced to secondary amines (5-6). The addition of a primary amine to imines with subsequent reduction of the adduct also leads to secondary amines (7-8). Secondary amines react similarly with the carbonyl compound (9-10) or with an imine (11-12), forming tertiary amines. The principal side reaction is the hydrogenolysis reaction of the carbonyl compound involving the formation of an alcohol (13). Apparently, the formation of the primary amine should proceed through steps (1) and (4), but there is evidence that secondary and tertiary amine precursors could be present at concentrations much higher than the amount of secondary and tertiary amine obtained at the end [1]. Thus, the reaction paths leading to the final product and, so, determining the selectivity of a particular catalyst under a set of reaction conditions are not clearly known.



Scheme 1. Reaction pathways in the reductive amination of carbonyl compounds (R, R’ = alkyl, aryl, H).

In homogeneous catalysis only a small number of reports [2-5] on the reductive amination of carbonyl compounds exist. Most of them describe complex catalysts [3-5] active in asymmetric reductive amination of prochiral ketones. The main disadvantage of the homogeneous processes is the relatively high value of catalyst loss. This inconvenience could be decreased by using solid catalysts (metal powders or supported metals).

There are numerous reports on the use of supported and unsupported Ni, Co and noble metal catalysts [1,6-14]. Metal sulfides (Re, Fe, Co, Ni, W, Pt, Rh) were also used [15-17] as catalysts in the reductive amination of ketones. The relative inactivity of these catalysts for the hydrogenation of the aromatic ring, ketones, nitriles, esters and other unsaturated functional groups, often permits useful selectivity in case of multifunctional compounds.

Methyl ethyl ketone [18] was chosen as test molecule because of lack of literature information concerning the reductive amination of this substrate with ammonia and hydrogen over supported noble metal catalysts.

EXPERIMENTAL

CATALYSTS: The catalysts tested in the reductive amination of methyl ethyl ketone (MEK) are presented in Table 1 together with some physicochemical characterization data as well. The charcoal supported catalysts contained 55-60% moisture. The quantitative values used for these samples refer to dry material.

Table 1

Catalysts characterization data (metal dispersions were calculated by using n_S values estimated according to literature [19])

Type of catalyst	S_{sp} (m^2/g)	S_M (m^2/g)	Metal location	Dispersion (%)	BET area (m^2/g)
5%Rh/charcoal	950	11.1	Intermediate	50.43	817.8
5%Rh/HSAgraphite	130	9.5	Surface	43.17	94.6
5%Ru/HSAgraphite.	130	8.0	Surface	43.78	41.6
5%Pd/HSAgraphite	130	11.4	Surface	51.10	87.6
5%Pt/HSAgraphite	130	5.0	Surface	40.48	80.1

HSA - high surface area

CATALYSTS TESTING: The reactions were carried out in batch reactors with a volume of about 65 ml. Magnetic stirring at a speed of 1100 rpm was used. The temperature inside the autoclave was measured by a thermocouple mounted on the lid of the autoclave. Weighed amount of catalysts were introduced into the autoclave. In order to assure a well-defined starting time for every reaction, the following experimental procedure was applied:

After addition of methyl ethyl ketone (MEK) and of the solvent (ethanol), the autoclave was flushed with nitrogen to remove the atmospheric oxygen. Ammonia was then added from the liquid ammonia cylinder at room temperature. Then the autoclave was placed in a thermostat bath preset to the reaction temperature. Adding hydrogen and completing fast to the working pressure occurred only after the preformed imine solution reached the desired reaction temperature (t = 0 is set for the time when the final pressure was established).

The progress of reaction in time was evaluated from the hydrogen consumption (added from a well known volume reservoire, V = 11.4 ml), keeping the working pressure in the autoclave constant by regulating a valve manually, or by measuring the hydrogen flow with a flow meter (BROOKS) having the pressure inside the autoclave controlled by a pressure regulator (BROOKS). Liquid sampling was used for monitoring the evolution of products in time.

Reductive amination of methyl ethyl ketone (>99%, Merck) were conducted mostly at 20-50 bar and 80 ˇC. The products were analyzed by using a Hewlett Packard 5890A gas chromatograph equipped with a DB Wax 1701 column and FID detector. Pure sec-butylamine and di-sec-butylamine were used for the identification of the main products in the reaction mixtures. GC/MS analyses were performed in order to identify reaction intermediates. The metal leaching was followed by XRF analysis of the filtered reaction mixtures.

Experiments were done in order to find whether mass transfer rate limitations occurred or not for the highly active catalysts. According to results obtained, mass transfer limitations of hydrogen diffusion from liquid to solid did not influence the measured reaction rates.

RESULTS AND DISCUSSION

In the product mixture resulted during the reductive amination of MEK with ammonia and hydrogen over supported noble metal catalysts we identified sec-butylamine, di-sec-butylamine and 2-butanol. Tri-sec-butylamine was never obtained. According to the analysis results, the reactions occurring in the reactor under the working conditions used ($V_{EtOH} = 8\ cm^3$, $n_{MEK} = 0.0222$ mol, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, $V_{EtOH}/V_{MEK} = 4$, p = 50 bar, T = 353 K) are given in Scheme 2.

$$\text{Me-CO-Et} + NH_3 + H_2 \rightarrow \text{Me-CH}(NH_2)\text{-Et} + H_2O$$

$$\text{Me-CO-Et} + \text{Me-CH}(NH_2)\text{-Et} + H_2 \rightarrow \text{Et-(Me)CH-NH-CH(Me)-Et} + H_2O$$

$$\text{Me-CO-Et} + H_2 \rightarrow \text{Me-COH-Et}$$

Scheme 2. Chemical reactions during the reductive amination of MEK.

In order to probe for mass transfer limitations, reductive amination experiments of MEK at different stirring speeds (1100 and 600 rpm), and at different catalysts concentrations were carried out. The experimental conditions and the results obtained for the reductive amination of methyl ethyl ketone on Rh/charcoal and Rh/HSA graphite catalysts are presented in Table 2.

Table 2

Experimental conditions and results for the reductive amination of MEK on charcoal and graphite supported rhodium catalysts at different stirring speeds.
n_M: moles of metal, $n_M = 1.11 \cdot 10^{-4}$ mol, Solvent: EtOH, $V_{EtOH} = 8$ cm^3, $n_{MEK} = 0.0222$ mol (2 cm^3), $n_{MEK}/n_M = 200$, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, $V_{EtOH}/V_{MEK} = 4$, p = 50 bar, T = 353 K.

Catalyst	t_{react} (min)	X (%)	Y_{pr} (%)	Y_{sec} (%)	$Y_{2\text{-}ol}$ (%)	r_{pr} (mol/mol· h)	r_{sec} (mol/mol· h)	$r_{2\text{-}ol}$ (mol/mol· h)
Rh/HSAgraph								
1100 rpm	60	97.6	85.7	0.4	11.9	171.5	0.7	23.9
600 rpm	65	97.9	84.8	0.7	9.9	169.6	1.3	19.8
600 rpm*	200	82.9	54.3	0.0	1.0	162.7	0.0	3.0
Rh/charcoal								
1100 rpm	8	99.2	98.5	0.4	0.6	1371.3	5.9	13.6
1100 rpm*	40	97.1	92.3	0.9	2.7	1383.8	40.8	12.7
600 rpm*	45	98.4	94.6	0.9	2.8	1261.6	36.8	11.3

X conversion (molar percentage of MEK converted to different products).
Y yield (molar percentage of MEK converted to the corresponding amine).
* $n_{Rh} = 2.22 \cdot 10^{-5}$ mol, $n_{MEK}/n_M = 1000$.

The results (conversions, yields, rates of formation) presented in Table 1 indicate that under the working conditions used, mass transfer limitations are unimportant.

Reductive amination of methyl ethyl ketone was done on the graphite and charcoal supported group VIII noble metal catalysts presented in Table 2. All of the reported experiments were carried out by adding hydrogen only after the preformed imine solution reached the desired reaction temperature. The filtered reaction products obtained on Rh and Pt were colorless, while those resulted on Pd and Ru catalysts were colored yellow. The XRF analysis (Philips PW 1480, wavelength dispersive X-ray fluorescence spectrometer) of colored mixtures indicate the presence of Ru and Pd in the solutions. At a detection limit of 0.002% rhodium was found not to dissolve, but the ruthenium loss of one catalytic cycle was noted to be 3-9 wt.% of the initial metal content.

Fig. 1 illustrates the hydrogen consumption as a function of time for the tested catalysts.

Fig. 1 shows that Rh/charcoal is the most active catalyst, followed by Pt/HSA graphite, Rh/HSA graphite, Ru/HSA graphite while Pd/HSA graphite being the less active catalyst.

The rates of formation of amines (primary and secondary) and 2-butanol normalized per mole of noble metal obtained for the reductive amination of methyl ethyl ketone are presented in Fig. 2.

Fig. 1. Hydrogen consumption versus reaction time during the reductive amination of methyl ethyl ketone on some graphite and charcoal supported group VIII noble metal catalysts. n_M: moles of metal, $n_M = 1.11 \cdot 10^{-4}$, Solvent: EtOH, $V_{EtOH} = 8\ cm^3$, $n_{MEK} = 0.0222$ mol, $n_{MEK}/n_M = 200$, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, p = 50 bar, T = 353 K.

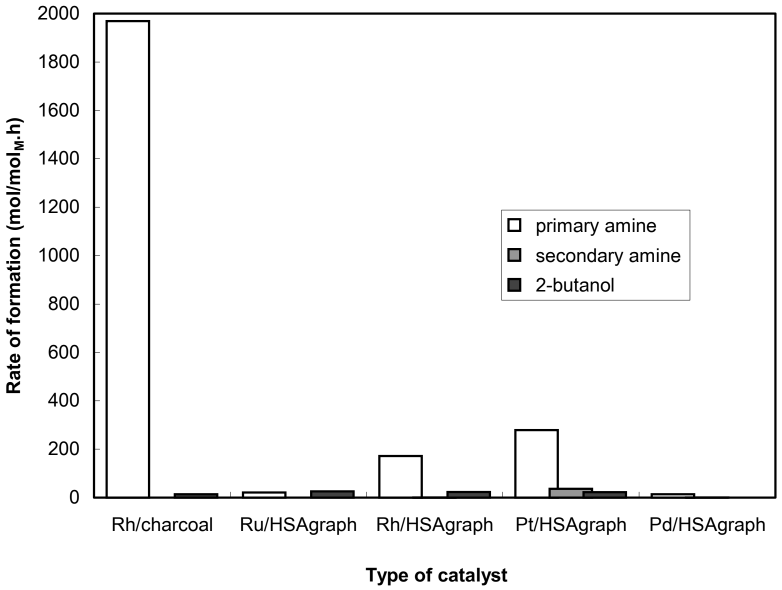


Fig. 2. Rates of formation of the sec-butylamine, di-sec-butylamine and 2-butanol during reductive amination of methyl ethyl ketone on supported group VIII noble metal catalysts. n_M: moles of metal, $n_M = 1.11 \cdot 10^{-4}$, Solvent: EtOH, $V_{EtOH} = 8\ cm^3$, $n_{MEK} = 0.0222$ mol, $n_{MEK}/n_M = 200$, $n_{NH3} = 0.3235$ mol, $n_{NH3}/n_{MEK} = 14.57$, p = 50 bar, T = 353 K.

One mole of Rh supported on charcoal produced ~12 times more sec-butylamine/hour than one mole of Rh supported on graphite. Rh/charcoal catalyst (with high metal dspersion and high BET area) was found to be not only the most active, but also the most selective catalyst. The graphite supported rhodium catalyst is less active and less selective, but in comparison to ruthenium and palladium has higher activity and selectivity. Pt/HSA graphite is an active catalyst, but has lower selectivity towards primary amine than Rh/HSA graphite.

In all the experiments 2-butanol was identified as a reaction product, in case of the Ru/HSA graphite catalysts even being the main component in the product mixture. However, the unwanted hydrogenolysis of MEK can be avoided by decreasing the pressure. Conducting the reductive amination of MEK at 20 bar, only traces of 2-butanol were detected in the product mixtures even by using Ru/HAS graphite as catalyst.

CONCLUSIONS

Among the studied catalysts the Rh and Pt based ones show the highest activity in reductive amination of methyl ethyl ketone. This observation underlines the major role of metal in determining the activity and selectivity of the supported catalysts.

The charcoal appears to be a good catalyst support providing high activity and selectivity for the supported Rh catalyst (having high BET area and high metal dispersion) and being significantly more active compared to Rh/graphite. This emphasizes the important role of the support materials.

The absence of tertiary amines during the reductive amination of methyl ethyl ketone can be attributed to the high sterical hindrance of branched amines.

At higher temperature and pressures (T = 353 K, p = 50 bar), the hydrogenolysis of methyl ethyl ketone to 2-butanol becomes a considerable secondary reaction, especially on graphite supported Ru catalysts.

Rhodium was found not to dissolve, but the XRF analysis indicates a non-negligible leaching of Ru and Pd during the reductive amination of MEK over Ru/HSA graphite and Pd/HSA graphite catalysts.

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